# Beam Halo Formation in High-Current Proton Beams

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# Early History of Beam Halo

- Beam loss was associated with existence of beam halo in LAMPF linac in 1970s.

- Beam halo was detected at end of LAMPF linac in 1975 (H. Koziol).

- Beam halo remained a mystery for almost 2 more decades.

- 100-mA CW Accelerator Production of Tritium (APT) project in 1990s provided motivation to understand beam halo and beam losses.

# Progress in understanding beam halo during past decade

- Theoretical framework for halo in linacs was developed from:
  - a particle-core model.
  - computer simulation.

- But no experiments had been done until the halo experiment on LEDA was carried out last year .

- Motivation for halo experiment was to test:
  - understanding of the physics.
  - the predictive capability of simulation codes.

# Particle-Core Model

- Mismatch of forces within beam excites collective beam modes driving transverse oscillations of core.

- Space-charge of oscillating core can drive particles in parametric resonance when $f_{particle} = f_{mode}/2$.

- Typically the particle amplitudes can grow to 6 or 7 rms beam widths over 30 to 40 mode-oscillation periods.

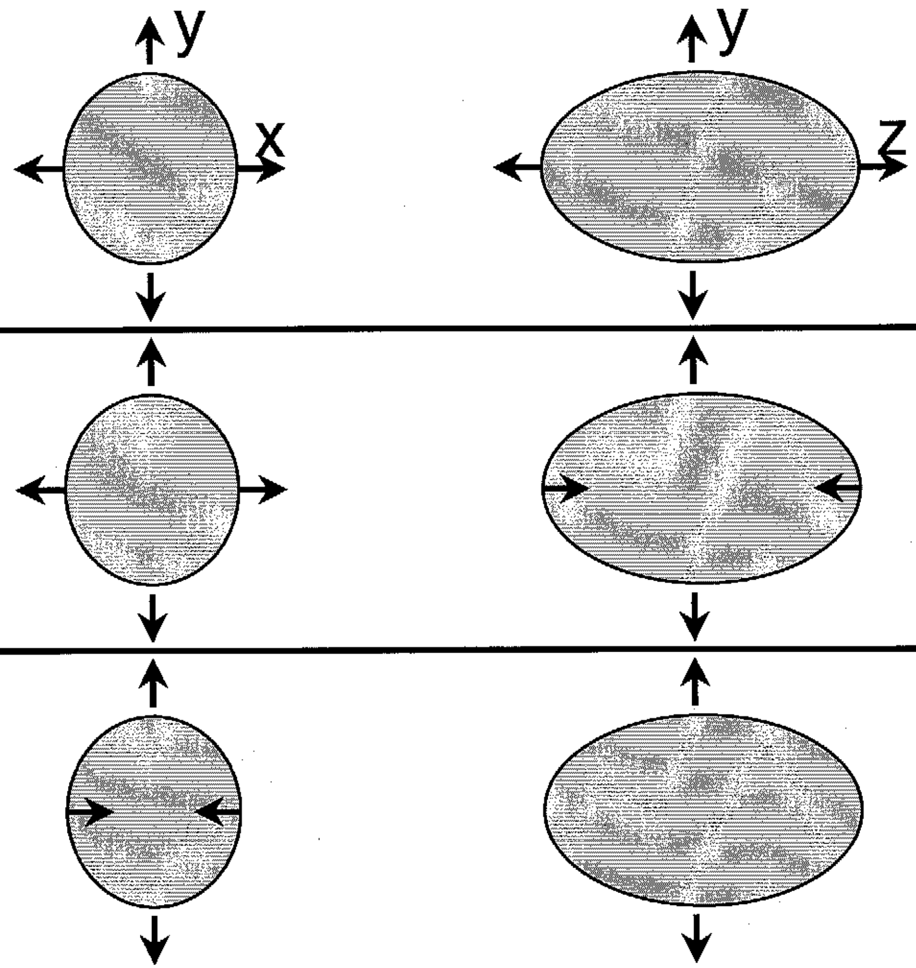
- Details of the beam dynamics require computer simulation.

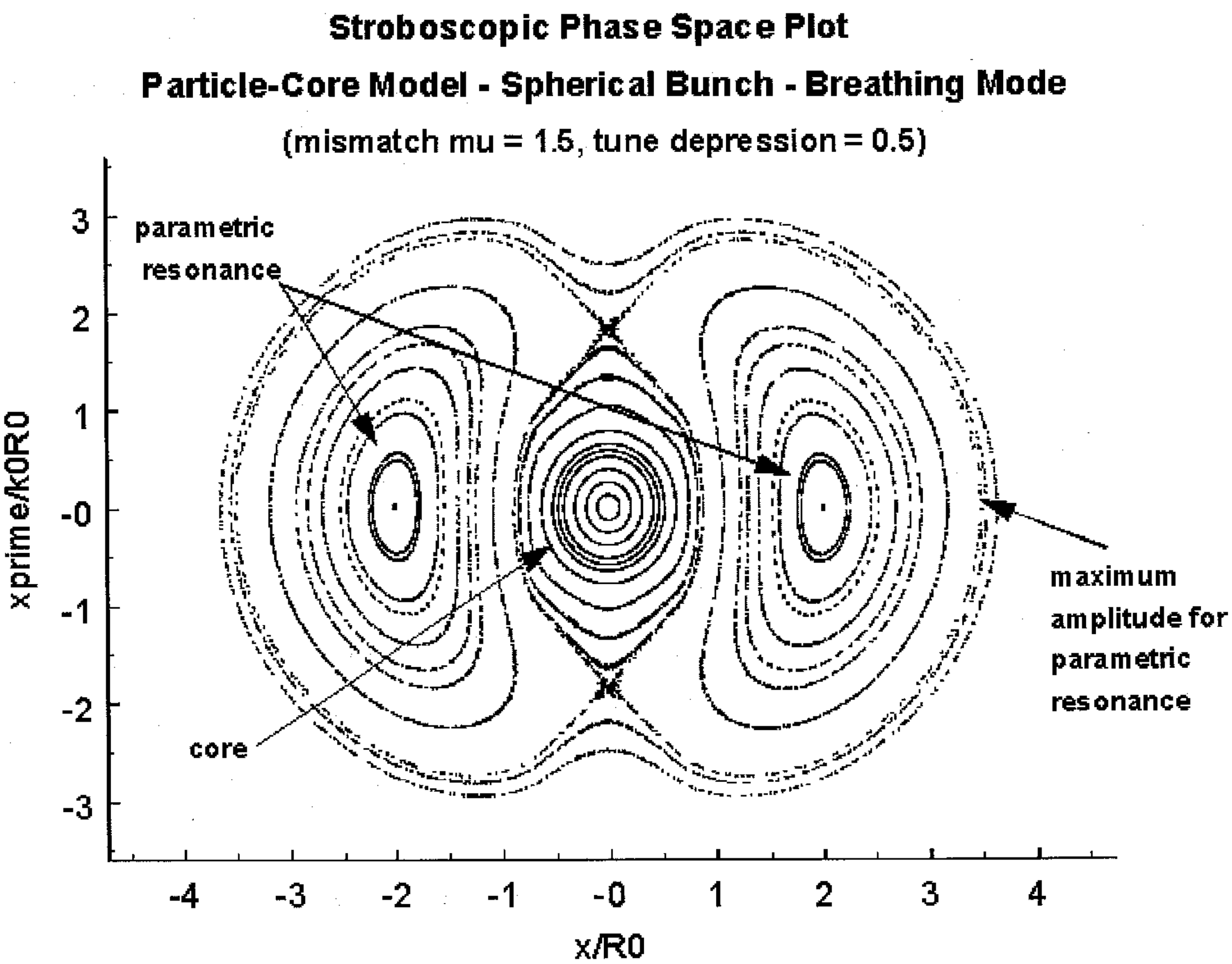
# Envelope Modes of Mismatched Bunched Beams

Symmetric (Breathing) Mode

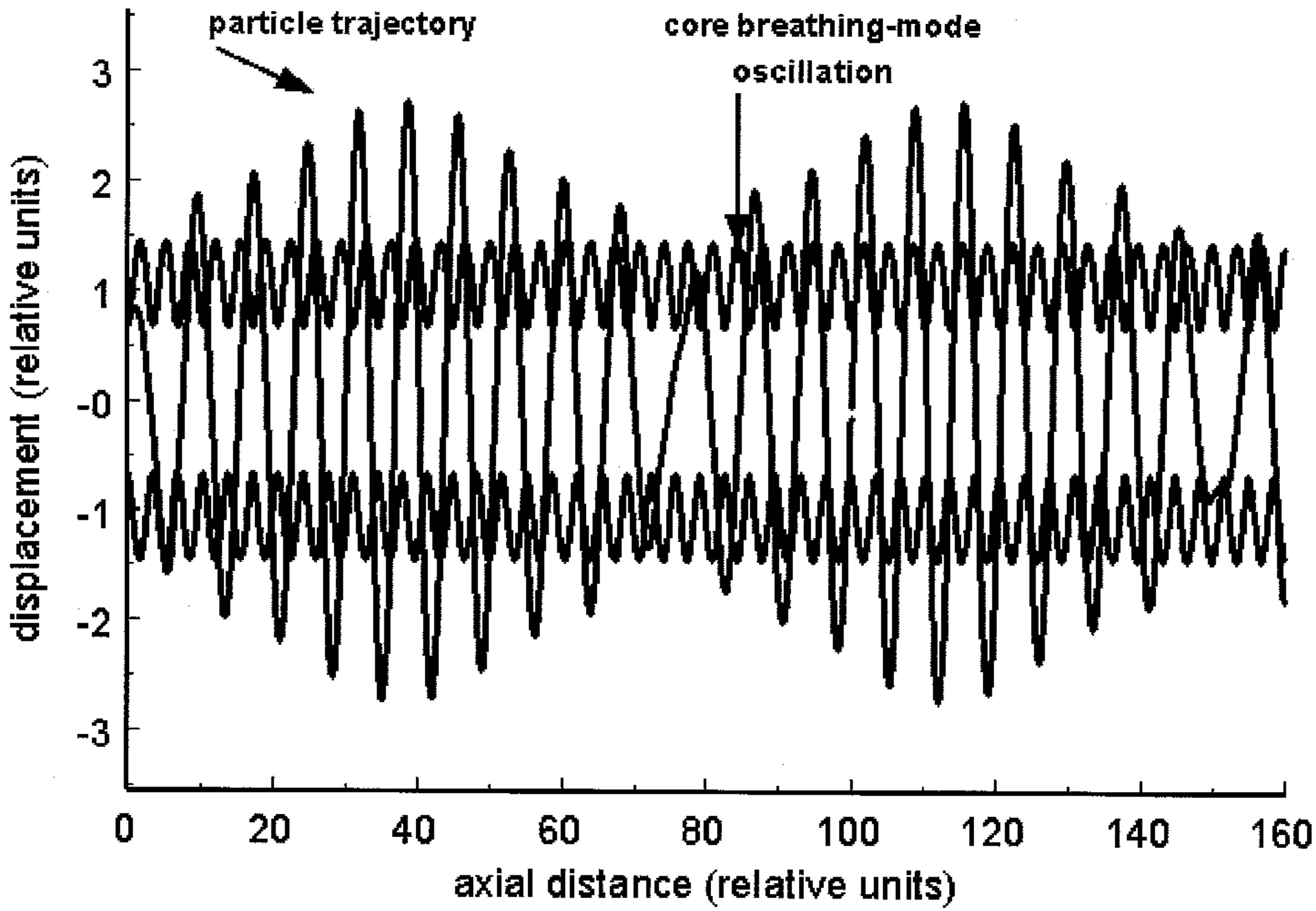
Antisymmetric Mode

Quadrupole Mode



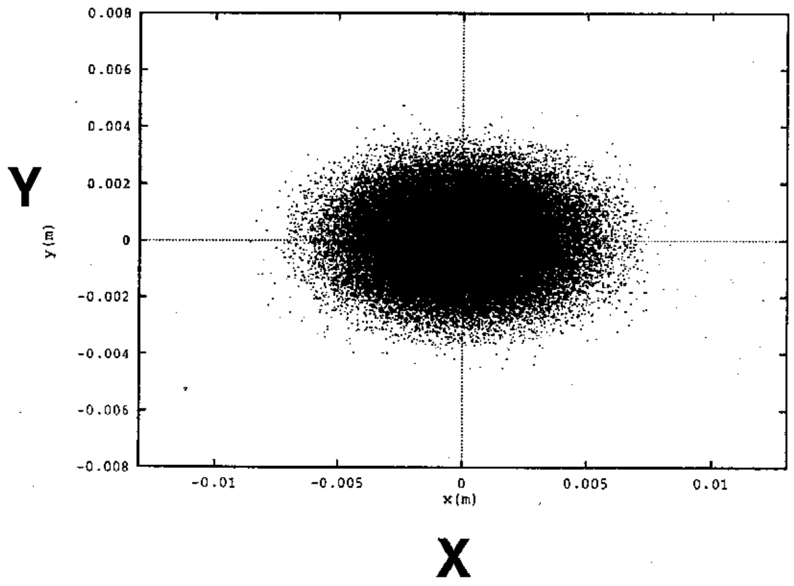

Stroboscopic Phase Space Plot
Particle-Core Model - Spherical Bunch - Breathing Mode
(mismatch mu = 1.5, tune depression = 0.5)
parametric resonance
core
maximum amplitude for parametric resonance
xprime/k0R0
x/R0
3
2
1
-0
-1
-2
-3
-4
-3
-2
-1
-0
1
2
3
4

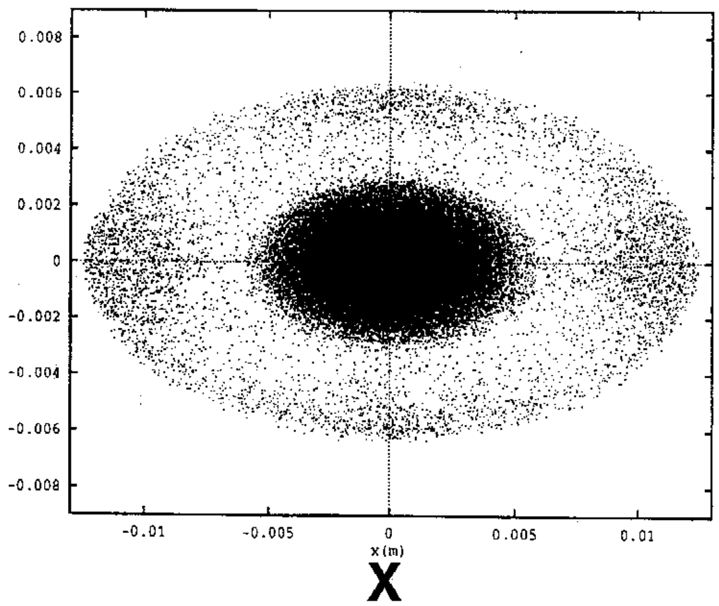
## Parametric Resonance in Sphere Particle-Core Model



# Computer simulations showed halo is formed in mismatched beams.

## Rms mismatched beam (on right) develops larger amplitudes than rms matched beam (on left).



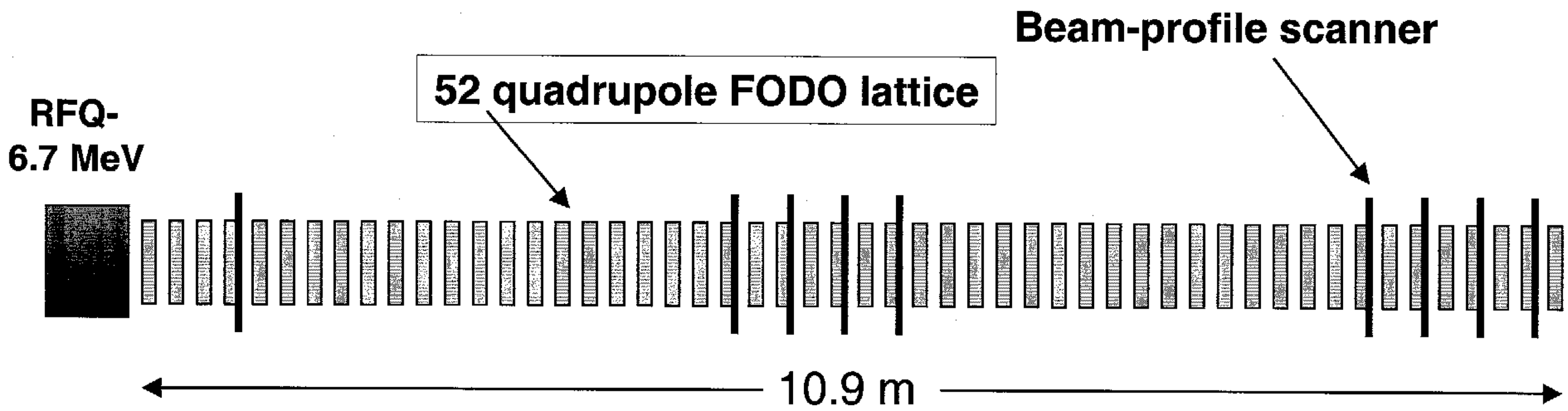
# Beam-halo experiment designed to test our understanding.

- Pulsed beam from 6.7-MeV LEDA RFQ into 52 quadrupole transport line. First four quadrupoles create mismatches.

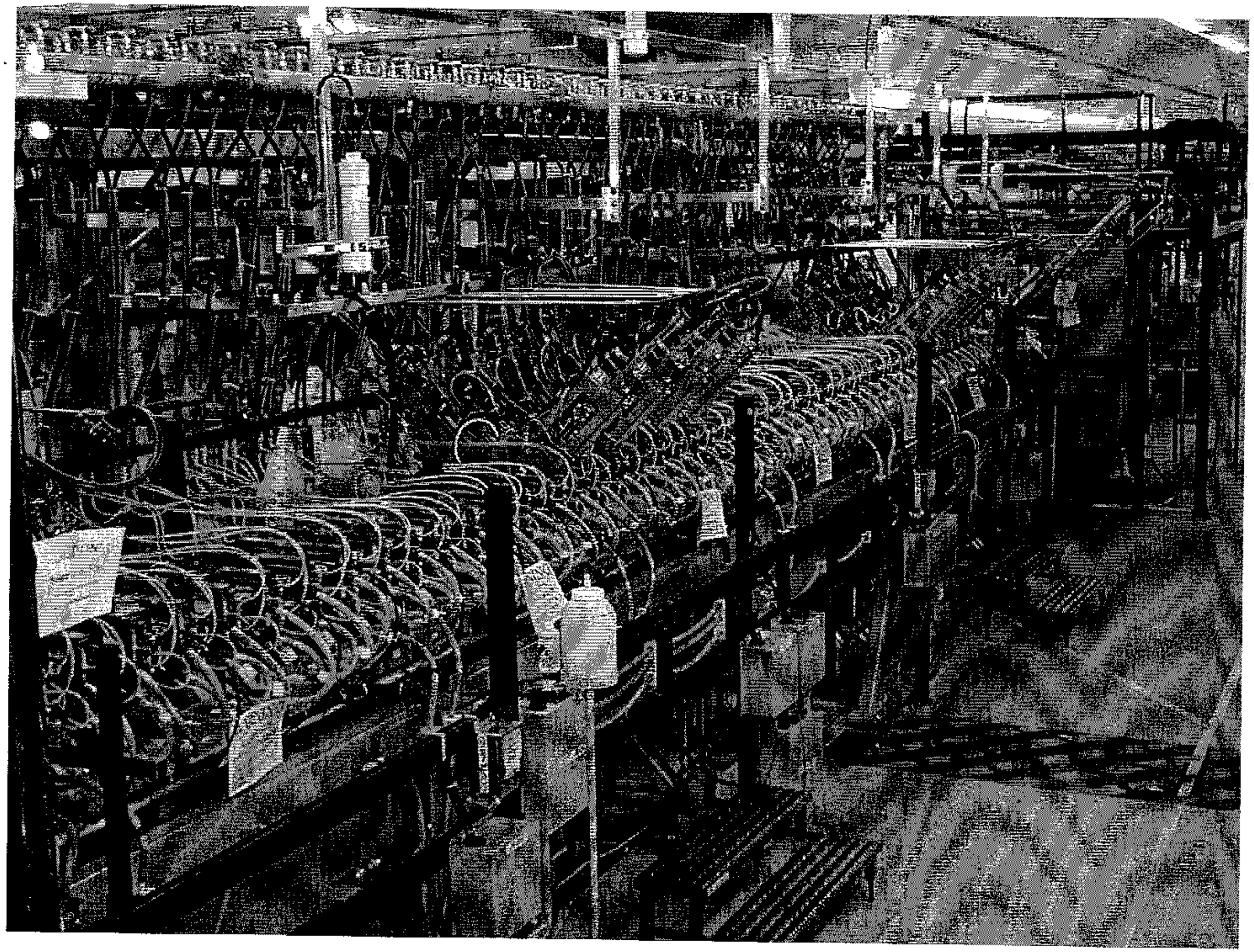
- 10 breathing-mode oscillations, enough to see initial stages of emittance growth caused by resonant halo-formation mechanism.

- Vary mismatch and current. Measure beam profiles to obtain: 1) rms emittances, 2) maximum detectable amplitudes.

# Beam-halo experiment



# 52 quad -11m beam channel after LEDA RFQ



# Implementation of the Experiment.

- Measurements between February and September, 2001 -- Six mismatch settings at 15, 50, 75, and 100 mA.

- New sensitive beam diagnostics gave excellent performance. Details of beam profiles never seen before.

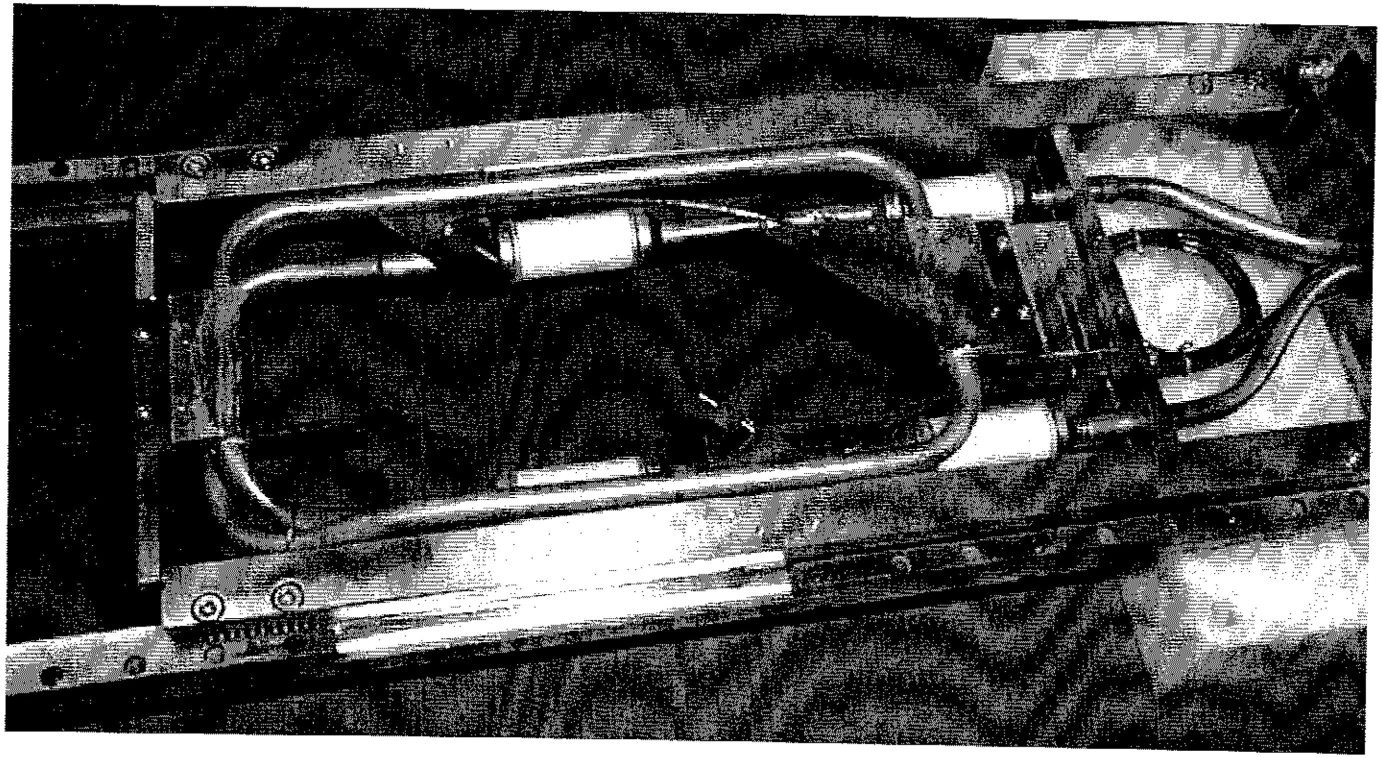
- Beam matching and mismatch procedures worked as designed.

- Analysis is now in progress.

# New state-of-the-art beam-profile diagnostics were designed and built for the halo experiment. (J.D.Gilpatrick, et al.)

- Three components mounted on common movable frame.
  - 33μ carbon wire to measure beam core.
  - Pair of graphite scraper plates for outer halo.
- Data from wire and scraper plates combined in computer software to produce single distribution with as much as $10^5$:1 dynamic intensity range.
- 9 measurement stations at which both horizontal and vertical profiles were measured.

# Wire and halo scraper assembly of the beam-profile diagnostic (J.D.Gilpatrick, et al.)



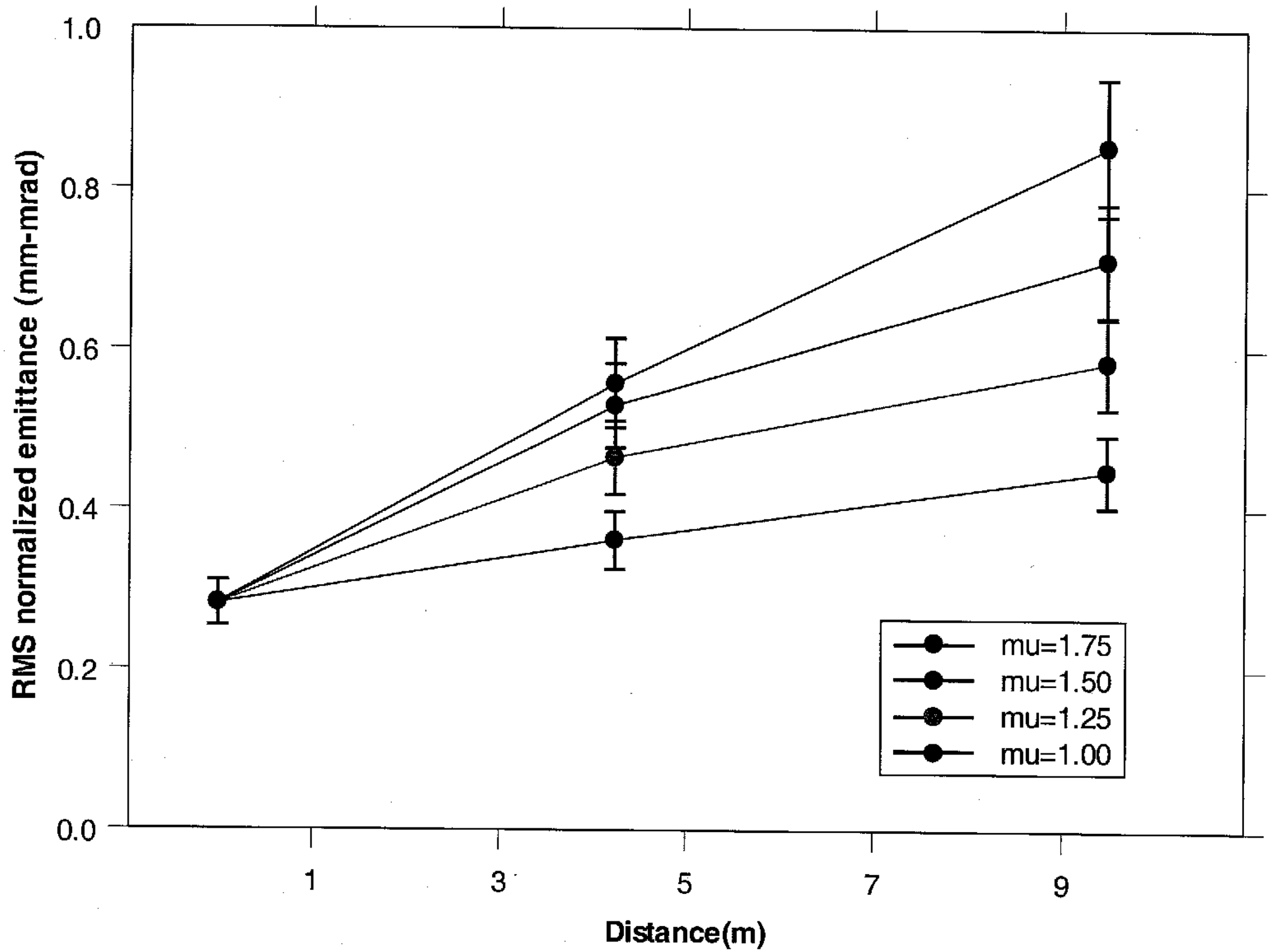
# What do we expect to see if the Particle-Core model is correct?

- Minimum emittance growth for matched beam.
- Emittance growth which increases with increasing mismatch.
- Emittance growth which increases along beam line.
- May see initial stages of growth in maximum detectable amplitude provided input beam is free of halo.

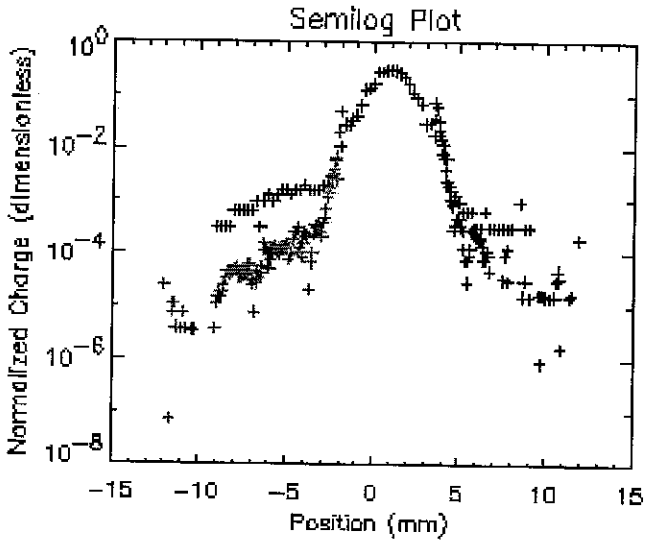
# Results are confirming general expectations of Particle-Core Model.

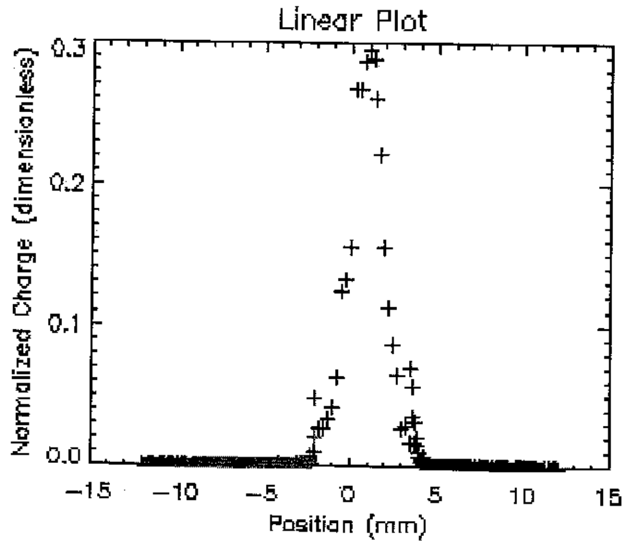
- Measured emittances were minimum for matched beams as expected.
- Emittances increased with increasing mismatch as expected.
- Emittances increased with increasing distance along beam line as expected.
- Maximum beam extent close to simulated values

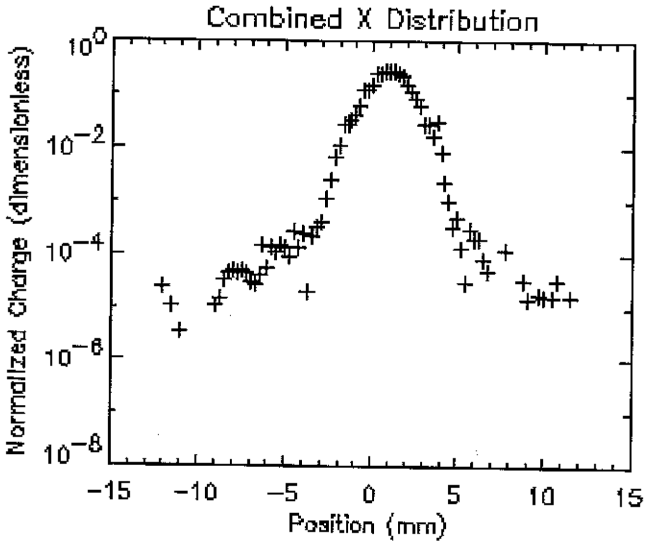
# X-Plane Rms Normalized Emittance Versus Distance



# Matched beam - 75 mA - scanner 51x




Calculated Moments of the Combined Distribution

File: /u2/optdvl/wshs_data/2001_May_2_22_31_z51.rws

Mean: 0.93145387 mm

Std Dev: 1.1019562 mm

Skew: −0.22773781

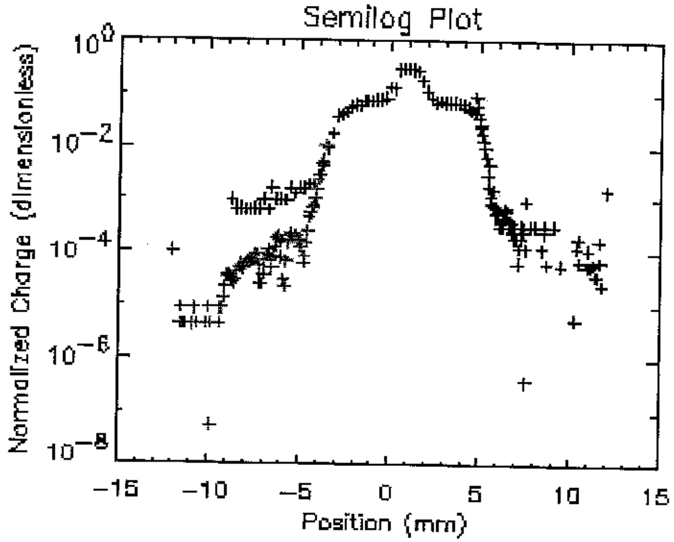
Kurtosis − 2: 1.3098605

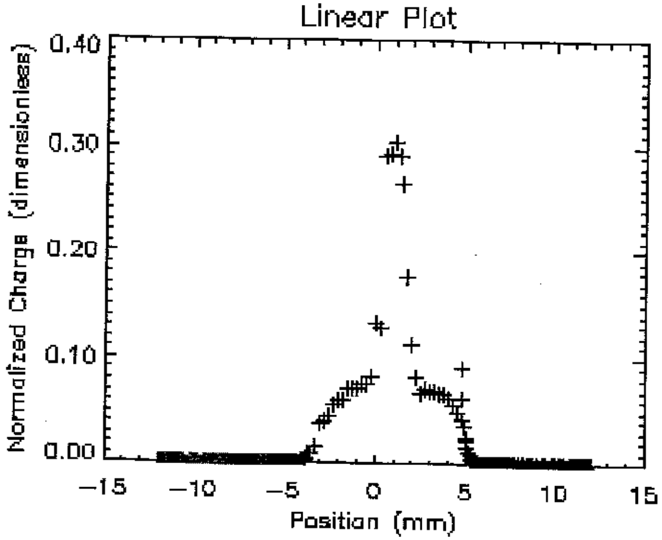
Where Signal to Noise > 2.5

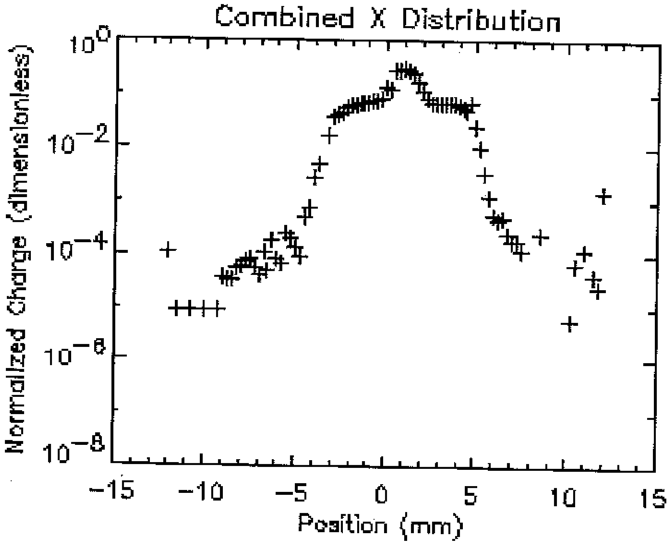
Negative halo scraper −8.32410 mm

Positive halo scraper 5.82570 mm

# Mismatched beam ($\mu$=1.5) - 75 mA - scanner 51x




Calculated Moments of the Combined Distribution

File: /u2/optdvl/wshs_data/2001_May_3_21_34_z51.rws

Mean: 1.0051845 mm

Std Dev: 1.8190567 mm

Skew: 0.039269982

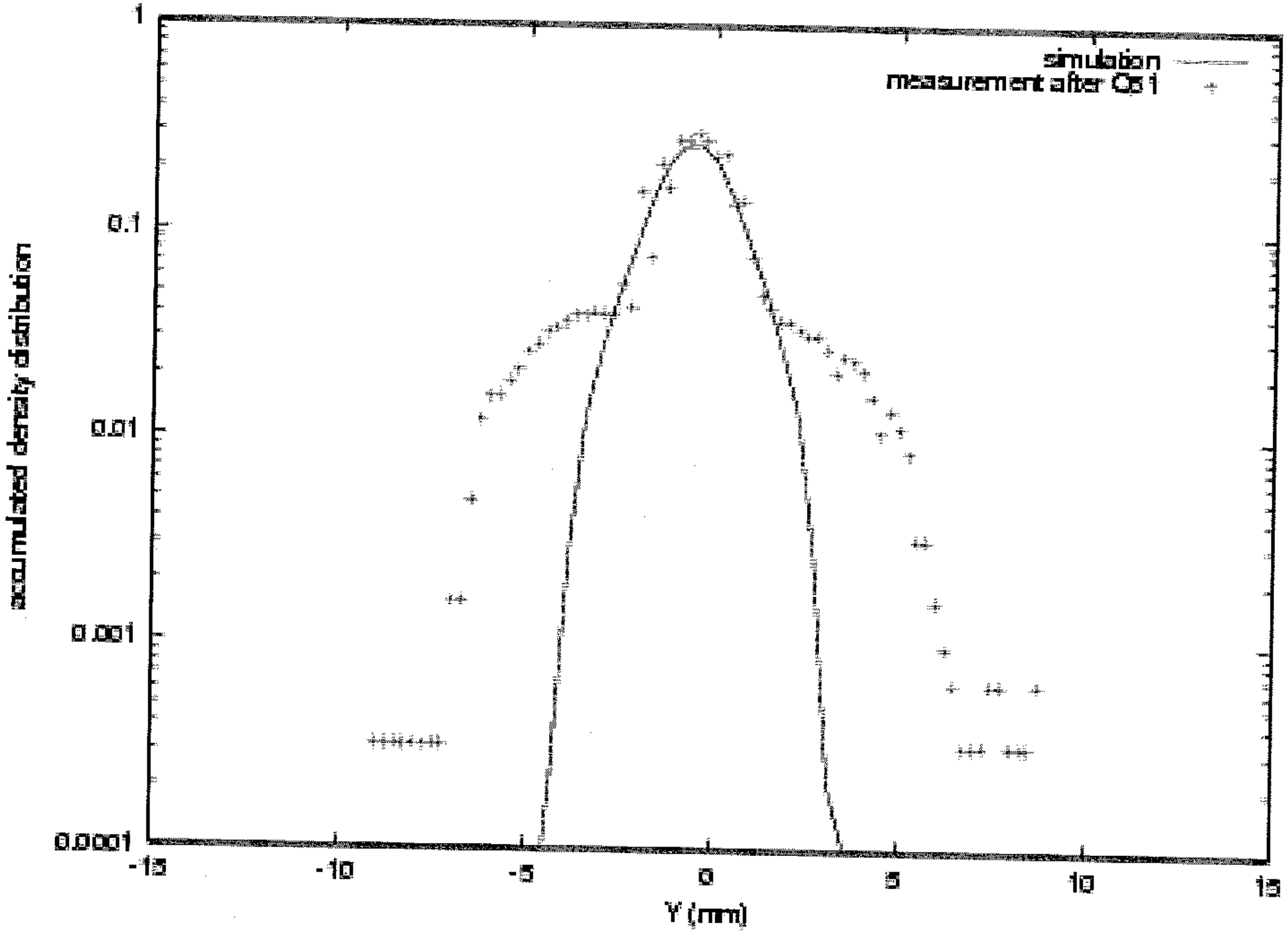
Kurtosis − 2: 1.5899716

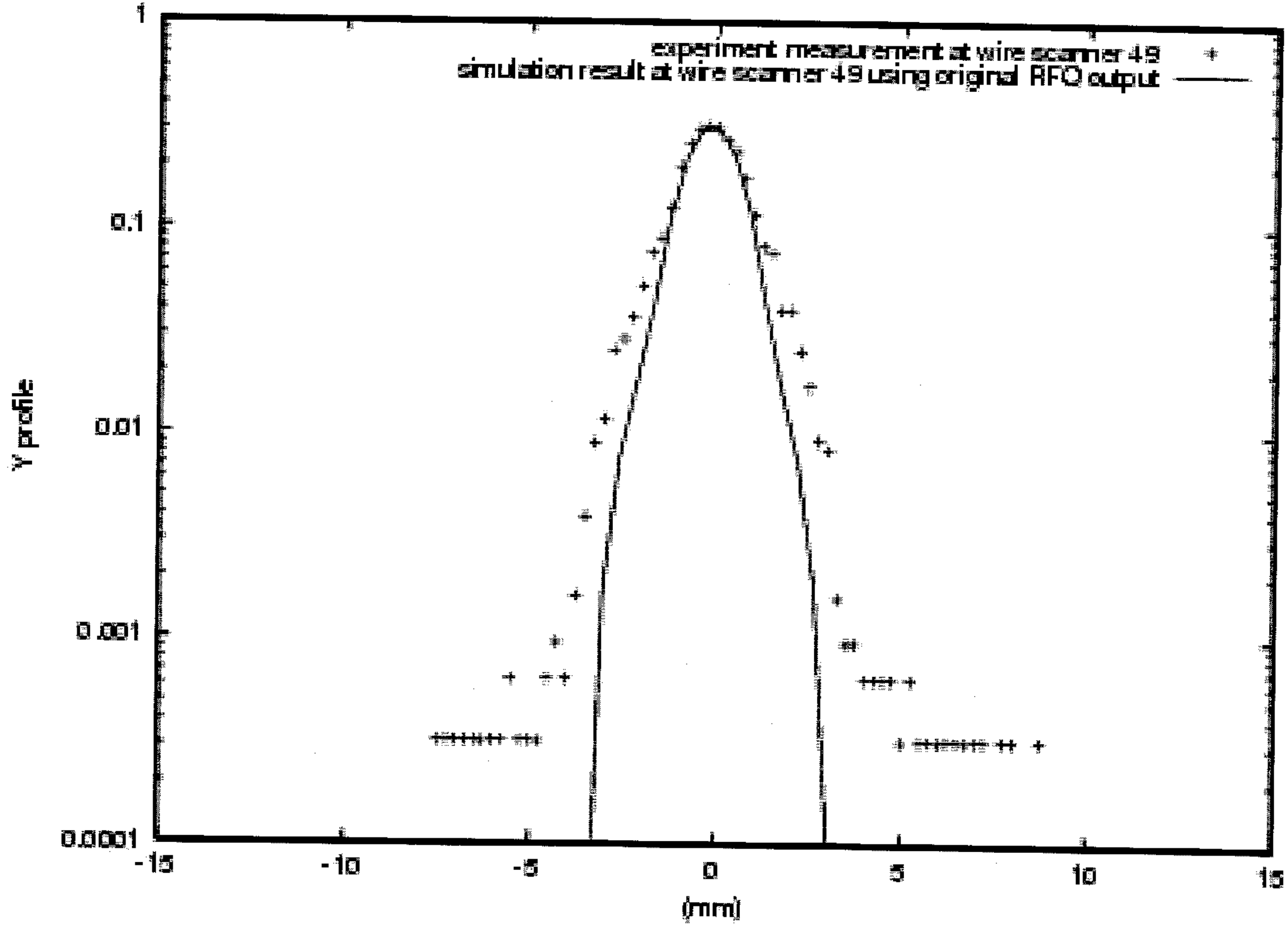
Where Signal to Noise > 2.5

Negative halo scraper −8.33130 mm

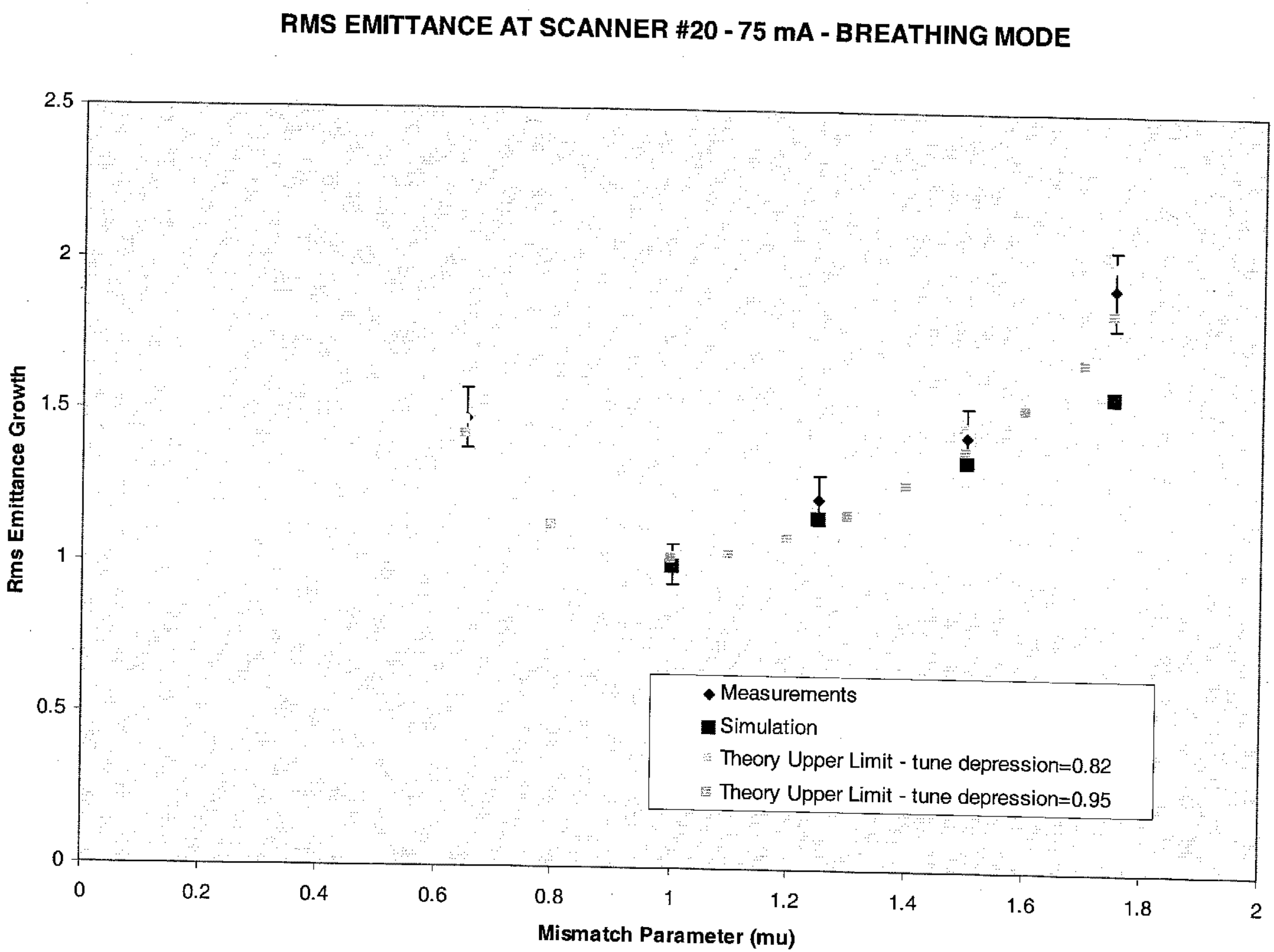
Positive halo scraper 5.91190 mm

# Comparison of shape of measured profile (points) with simulation (curve) for mismatched case ($\mu$=1.5) at scanner 51



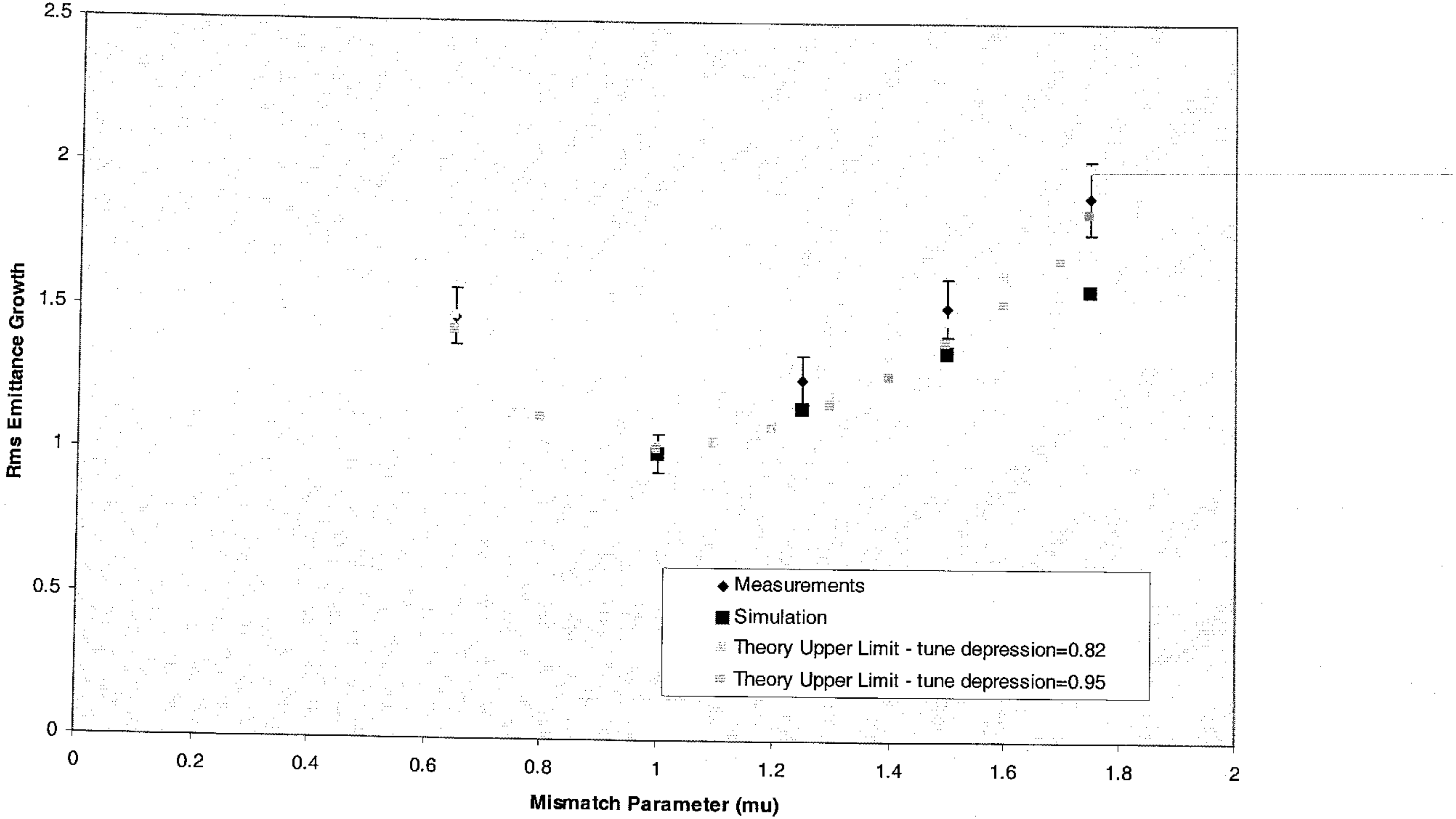


experiment measurement at wire scanner 49
simulation result at wire scanner 49 using original RFQ output
Y profile
1
0.1
0.01
0.001
0.0001
-15
-10
-5
0
5
10
15
(mm)



RMS EMITTANCE AT SCANNER #20 - 75 mA - BREATHING MODE
Rms Emittance Growth
Mismatch Parameter (mu)
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Measurements
Simulation
Theory Upper Limit - tune depression=0.82
Theory Upper Limit - tune depression=0.95

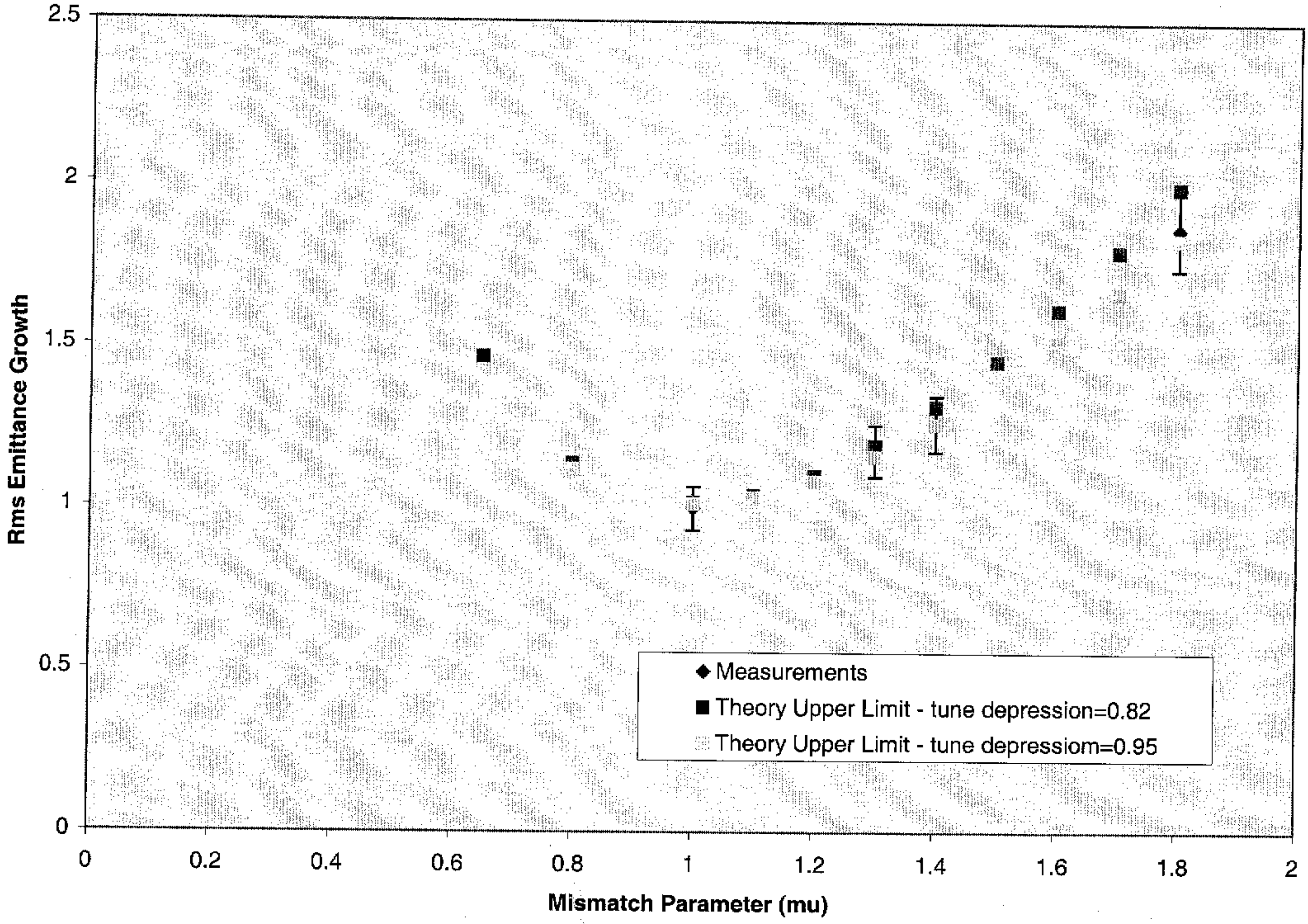
RMS EMITTANCE GROWTH AT SCANNER #45 - 75 mA - BREATHING MODE



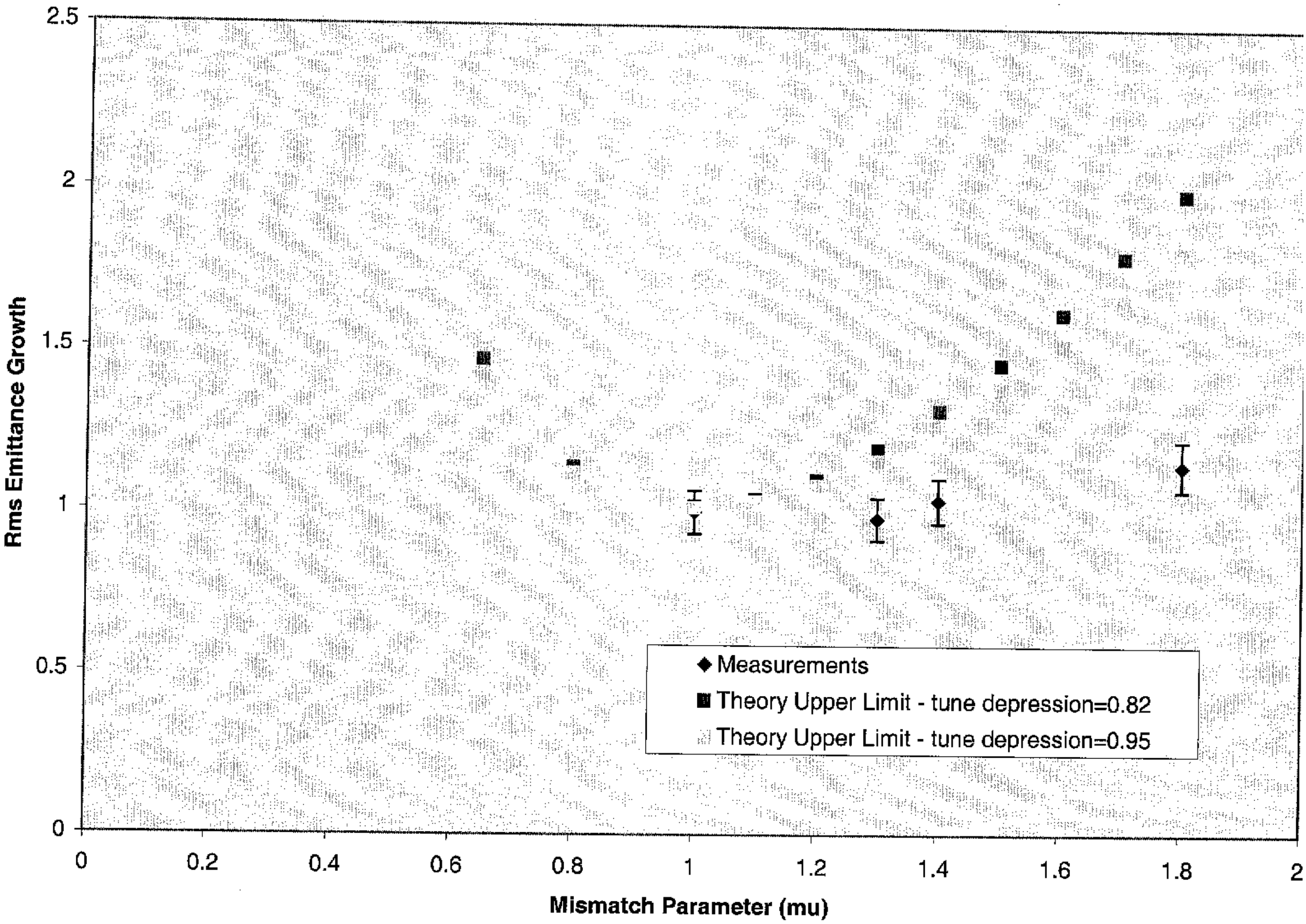
# The experiment is also providing new and unexpected results.

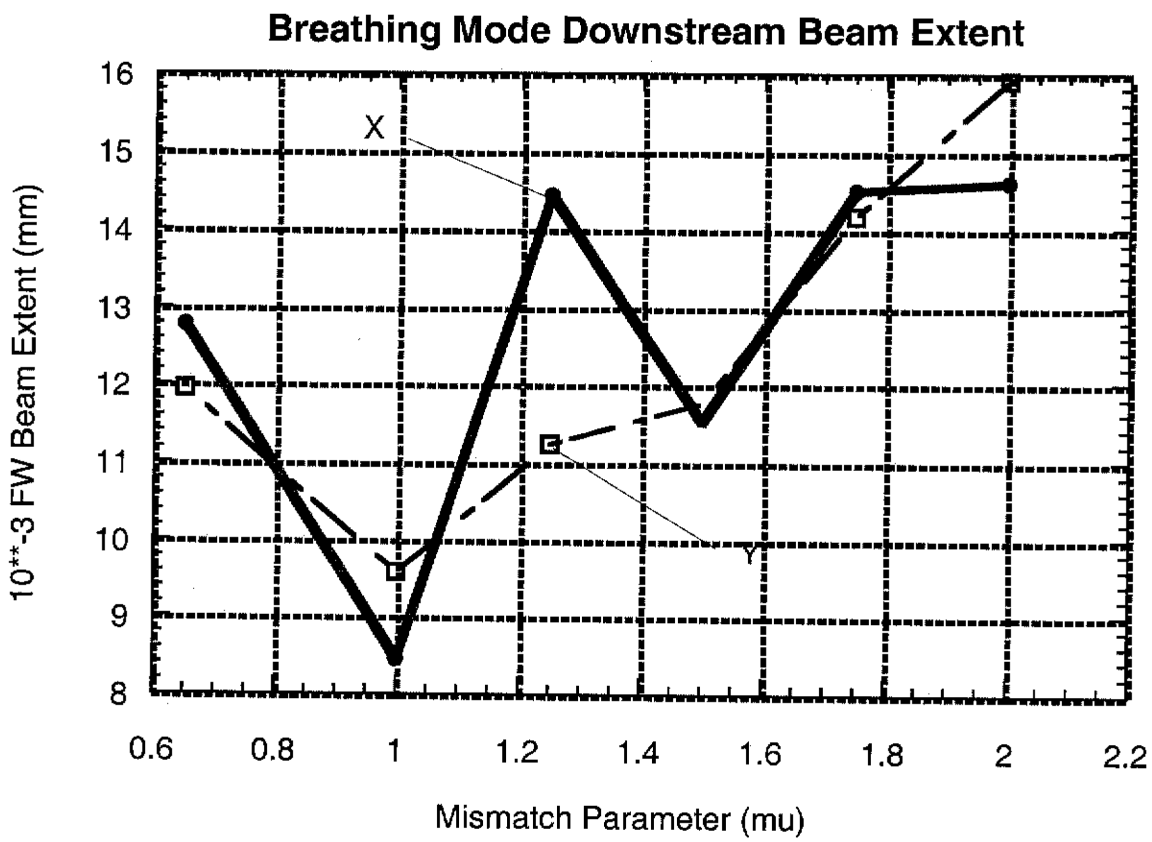
- **Maximum detectable amplitudes for matched beams are larger than we expected.**
  -suggests halo in input beam.
- **Beam profiles for mismatched cases show unexpected shoulders.**
  -suggests nonlinear aberrations of unknown origins.
- **Most realistic simulation so far** (Young, Qiang), **beginning at ion source, underestimates widths and shoulders.**
  - Profiles from simulation are ~30% or more too narrow.
  - Beam sizes from simulation are ~30% or more too small.
  - Rms emittances from simulation are also too small.

## RMS EMITTANCE GROWTH AT SCANNER #45 -75 mA - QUADRUPOLE MODE



## RMS EMITTANCE GROWTH AT SCANNER #20 - 75 mA - QUADRUPOLE MODE





Breathing Mode Downstream Beam Extent
10**-3 FW Beam Extent (mm)
16
15
14
13
12
11
10
9
8
X
Y
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
Mismatch Parameter (mu)

# What do we conclude from an initial look at the rms emittance growth at 16, 75, and 100 mA?

- Consistent with minimal matched-beam emittance growth between the two scanner clusters as expected.

- Mismatch emittance growth generally increases with increasing mismatch (deviations of $\mu$ from 1) as expected.

- Mismatch emittance growth is larger at same or larger at final scanner cluster than at middle cluster as expected.

- Average of x and y emittance growth consistent with maximum allowed by free energy.

- **Surprising: Rms emittance growth consistent with almost total transfer of free energy to emittance at all currents in just 10 oscillation cycles.**

# Conclusions

- The new beam-profile diagnostic has opened a **new regime for observing beam halo** to densities as low as $10^{-5}$ of the core density.

- Initial results show nearly complete free energy transfer to emittance growth in only 10 oscillation periods.
  The emittance growth mechanism is very effective.

- **Rms emittance growth results are consistent with a very strong halo and emittance-growth mechanism that the resonant Particle-Core (2:1 resonance) Model provides, but no direct proof. (There is no alternative model at present.)**

- A **~~Major~~ challenge for simulation is to** predict **~~understand~~ the input phase space distribution needed to explain the results.**